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Infrared Reflectances of Metals at Cryogenic Temperatures-A Compilation From the Literature

P. F. DICKSON AND M. C. JONES

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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P. F. Dickson and M. C. Jones

Spectral and total reflectances for metals at cryogenic temperatures in the infrared wavelength region are compiled from the literature. Information concerning sample preparation and purity, radiation source, and methods of reflectance measurement are also presented. Observations regarding the effects on reflectance of temperature, oxide layer, wavelength, and sample preparation are given .

Key Words: Compilation, cryogenic, infrared, metals, reflectance.

1. Introduction

Calculation of radiative heat transfer at cryogenic temperatures requires a knowledge of thermal radiative properties of materials at these temperatures. From the nature of thermal radiative processes at low temperatures it is evident that one needs data in the infrared, and in particular in the far infrared. This can be seen from Wien's displacement law for a black body ($\lambda_{max} T = 2898\,\mu\,°K$). The wavelength of maximum emitted radiative energy shifts from $\lambda \cong 9.8\,\mu$ at room temperature ($T = 295°K$) to $\lambda \cong 725\,\mu$ at 4°K. This survey comprises information, summarized here in graphical and tabular form, currently available in the infrared wavelength region (through mid-1966) on thermal radiative properties of metals, in particular, reflectances, at cryogenic temperatures.

The survey was undertaken as a preliminary to an experimental program. As will be evident, very little work has been done in the far

infrared, the only reported measurements beyond 14 μ being those of Aronson, et al. [1964] on stainless steel, an aluminum alloy, a magnesium alloy, and chromium. The ±5% error quoted by these authors serves to underline the difficulty of making reflectance measurements on highly reflecting materials in the far infrared by conventional spectrophotometric techniques.

Theoretical considerations and experimental techniques in determining optical constants of metals were reviewed by Givens [1958] and Ehrenreich [1965], and a review of the subject at low temperatures was given by Corruccini [1962]. Previous surveys on total emissivity data at low temperature have been given by Fulk and Reynolds [1957a] and Corruccini [1957].

Since the surveys of Fulk and Corruccini were published (containing no spectral data at low temperatures) several spectral studies have appeared in the literature. Along with this aspect there has also been an apparent realization by the same workers that the older data in the literature are of little more than qualitative interest due to their irreproducibility; the reflectance of a metallic surface depends strongly on the method by which it was prepared. Much effort has gone into producing surfaces of high purity with no work-hardened surface layer present. This has culminated in the highly reproducible pure metallic surfaces produced by ultra-high-vacuum vapor deposition ($\sim 10^{-10}$ mm Hg) by Bennett at the Michelson Laboratory. The room temperature reflectances of these surfaces are higher than what had previously been achieved. They are discussed and used below as a comparison with the work of other authors to illustrate the effects of both temperature and surface preparation. Such was the improvement in room temperature reflectances obtained by the use of ultra-high-vacuum vapor deposition that one can only regret, as yet, no similar measurements have been

reported at low temperature and longer wavelength where even higher reflectances are to be expected. Rate of deposition also has an effect on reflectance as indicated by Bennett, Silver, and Ashley [1963], with greater reflectance values obtained for increased deposition rates.

In view of this later work it has seemed desirable to present the results of this compilation in two sections. Section 2 consists of all spectral data reported and contains only one work published before 1959. Section 3 contains total reflectance data and is mostly older data, some of which were reviewed previously by Fulk and by Corruccini. However, original references are given where known. The word "total," as here applied to reflectance, means the value obtained by integration over all wavelengths. It should be remembered that this value is dependent on the wavelength distribution of incident flux.

The total or spectral reflectance (ρ_t or ρ_λ) of a surface may be obtained by a number of direct experimental techniques. It may also be obtained indirectly for an opaque surface from a measurement of the absorptance (α_t or α_λ), for then $\rho = 1 - \alpha$. A second indirect method is to calculate the normal reflectance ($\rho_{\lambda,0}$) from measurements of the refractive index n_λ and the absorption coefficient k_λ by use of the Fresnel formula

$$\rho_{\lambda,0} = \frac{(n_\lambda - 1)^2 + k_\lambda{}^2}{(n_\lambda + 1)^2 + k_\lambda{}^2} .$$

Measurements of the total or spectral emittance (ϵ_t or ϵ_λ) have also been used in the past by invoking Kirchoff's law: $\alpha_t = \epsilon_t$ and $\alpha_\lambda = \epsilon_\lambda$. Recently, however, a theoretical question has arisen as to the general applicability of Kirchoff's law [Ashby and Schocken, 1964], and this

seems to be particularly important at long wavelengths and low temperatures.

In the tables and graphs which follow, reflectances are reported as such when they are either from direct measurements or derived from measurements of α or n and k; reflectances are not derived from emittance measurements. Reflectances are normal (ρ_0) unless otherwise stated. It may be noted that in the limit of zero absorptance the ratio of hemispherical to normal absorptance approaches the value 4/3 for metals [Jakob, 1949].

The methods by which data were obtained are indicated in the tables below by the following general classification:

Method 1. Direct measurement of normal reflectance by multiple reflection techniques.

Method 2. Direct measurement of normal reflectance or absorptance by calorimetric techniques.

Method 3. Calculation, by either the original authors or the present authors, of normal reflectance from optical constants n and k determined by:
(a) measurements of absorptance at oblique incidence for two polarization components (perpendicular and parallel to the plane of incidence) by a calorimetric technique, or
(b) measurement of the phase shift and relative magnitudes of the perpendicular and parallel components of a reflected beam at oblique incidence.

Method 4. Measurement of absorptance or emittance by rate of boil-off of a cryogenic liquid. This method gives total hemispherical values.

Method 5. Direct measurement of normal emittance by comparison of emitted radiation with that emitted by a black body at the same temperature.

These general experimental techniques are referred to in the tables, and any variations, when applicable, are noted.

Information as to type of radiation source (e. g., monochromatic, wavelength band, total radiation from a source at a given temperature) accompanies the data. Techniques of surface preparation are also given.

The temperature region of primary interest was that below 100°K; therefore, only those metals for which data were available in this region are presented. However, for comparison and completeness, selected data on these materials at room temperature are also given if available.

Theory predicts that the reflectance of a metal in the infrared region will increase with decreasing temperature and increasing wavelength. Also, surface preparation is known to have a significant effect on reflectance values obtained. Results of this survey indicate that reflectance increases for preparation techniques in the following order: mechanical polishing, high vacuum vapor deposition, electropolishing, and ultra-high-vacuum deposition. Oxidation or impurities on the surface layer generally decrease reflectance, but the effect seems much smaller for oxidation than previously believed. Alloys have lower reflectances than pure metals. Although data available on any metal listed are not complete enough for a quantitative check, reflectances given tend to follow the aforementioned expectations.

2. Spectral Reflectance

Of particular current interest are data on reflectance as a function of wavelength (spectral reflectance, ρ_λ). Effects on reflectance of surface preparation, temperature, and alloy composition may also be observed in the graphs and tables which follow. Results show that, to obtain reproducible results, care must be taken to define surface preparation as well as other experimental techniques.

2.1 Aluminum

Variation of normal spectral reflectance ($\rho_{\lambda,0}$) with temperature, deposition vacuum, and wavelength is well illustrated for aluminum in figure 2.1. As is seen, reflectance of ultra-high vacuum ($\sim 10^{-10}$ mm Hg) evaporated films [Bennett, et al. 1963] is significantly higher than those values obtained using the usual high vacuum ($\sim 10^{-6}$ mm Hg) techniques. Room temperature reflectances of high-vacuum deposited films calculated from the optical constants of Golovashkin, et al. [1960] and measured directly by Bennet, et al. [1962] show excellent agreement.

Bennett, et al. [1962] state that, contrary to popular belief, the oxide layer formed on aluminum has almost no effect on the infrared reflectance. Calculations on oxide layers from 10 to 100 Å thick show the change in reflectance to be less than 0.1% for $\lambda > 1.5$ μ. A 22 Å-thick film is reported formed after several weeks' exposure.

TABLE 2.1 SPECTRAL REFLECTANCE OF ALUMINUM

Reflectance				Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda, 0}$ T = 78°K	$\rho_{\lambda, 0}$ T = 295°K		Vacuum deposition (no magnitude given)	Monochromatic	3(b)	Golovashkin, Motulevich, and Shubin [1960]
0.8	0.9156	0.8894		Sample purity: 99.99%			
0.9	0.9424	0.9211					
1.2	0.9734	0.9604					
1.5	0.9791	0.9698					
2.0	0.9803	0.9738					
2.5	0.9830	0.9762					
3.0	0.9844	0.9775					
4.0	0.9861	0.9794					
5.0	0.9879	0.9818					
6.0	0.9875	0.9817					
7.0	0.9870	0.9819					
8.0		0.9829					
9.0		0.9806					
$\lambda(\mu)$	$\rho_{\lambda, 0}$(uhv)	$\lambda(\mu)$	$\rho_{\lambda, 0}$(uhv)	uhv = vacuum deposition at 10^{-10} mm Hg	Monochromatic	1	Bennett, Silver, and Ashley [1963]
0.300	0.9208	3	0.9805	Sample purity = 99.999%			
0.350	0.9205	4	0.9826	T = Room temperature			
0.400	0.9194	5	0.9843				
0.450	0.9175	6	0.9856				
0.500	0.9162	7	0.9866				
0.550	0.9157	8	0.9872				
0.600	0.9117	9	0.9874				
0.650	0.9057	10	0.9876				
0.700	0.8977	11	0.9879				
0.750	0.8862	12	0.9882				
0.775	0.8773	13	0.9884				
0.800	0.8676	14	0.9886				

Reflectance						Sample Preparation	Radiation Source	Method	Reference
0.825	0.8657		16	0.9892					
0.850	0.8677		18	0.9896					
0.875	0.8744		20	0.9902					
0.900	0.8908		22	0.9907					
0.925	0.9075		24	0.9912					
0.950	0.9243		26	0.9918					
1.000	0.9402		28	0.9923					
1.200	0.9637		30	0.9928					
1.500	0.9742		32	0.9933					
2.000	0.9779								
$\lambda(\mu)$	$\rho_{\lambda,0}$ (fresh)	$\rho_{\lambda,0}$ (aged)	$\lambda(\mu)$	$\rho_{\lambda,0}$ (fresh)	$\rho_{\lambda,0}$ (aged)	Vacuum deposition at 10^{-5} mm Hg.	Monochromatic	1	Bennett, Bennett, and Ashley [1962]
0.550	0.9094	0.9049	5	0.9812	0.9772	fresh = freshly deposited.			
0.600	0.9048	0.9021	6	0.9823	0.9784	aged = aged in air for several weeks.			
0.650	0.8989	0.8976	7	0.9831	0.9794	Sample purity: 99.998%			
0.700	0.8900	0.8886	8	0.9837	0.9801	T = Room temperature			
0.750	0.8761	0.8761	9	0.9841	0.9807				
0.775	0.8678	0.8678	10	0.9845	0.9812				
0.800	0.8604	0.8596	11	0.9849	0.9816				
0.825	0.8569	0.8556	12	0.9854	0.9821				
0.850	0.8622	0.8596	13	0.9857	0.9826				
0.875	0.8759	0.8730	14	0.9861	0.9830				
0.900	0.8920	0.8894	16	0.9868	0.9838				
0.925	0.9072	0.9030	18	0.9873	0.9845				
0.950	0.9192	0.9154	20	0.9878	0.9852				
1.000	0.9360	0.9324	22	0.9883	0.9856				
1.200	0.9596	0.9585	24	0.9887	0.9861				
1.500	0.9676	0.9658	26	0.9890	0.9864				
2.000	0.9718	0.9699	28	0.9893	0.9867				
3.000	0.9765	0.9736	30	0.9896	0.9870				
4.000	0.9795	0.9758	32	0.9898	0.9872				

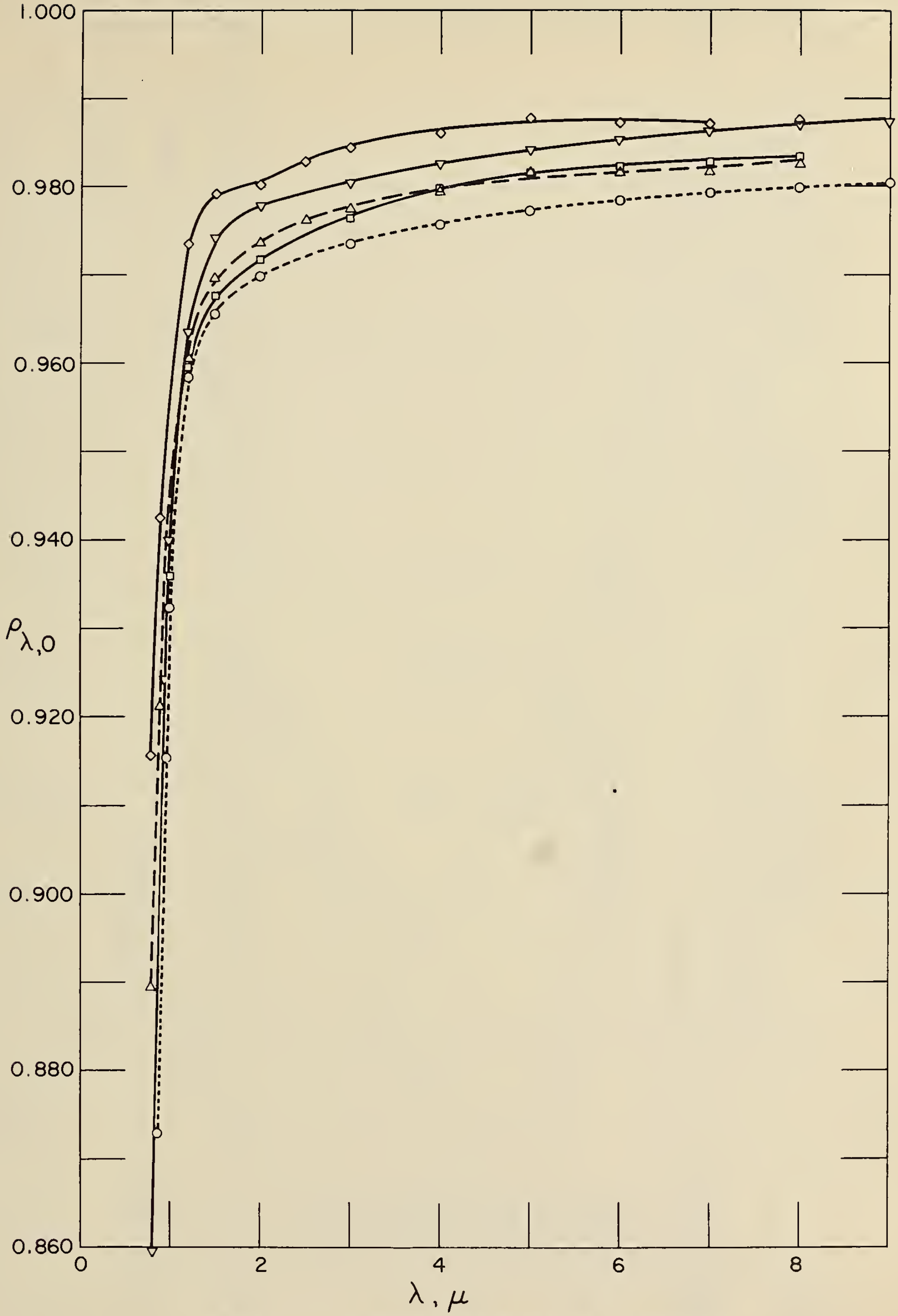

Figure 2. 1 Spectral reflectance of aluminum

◇ T = 78°K } Golovashkin, Motulevich, and Shubin (1960)
△ T = 295°K }

▽ T = room temp (10^{-10} mm Hg deposition) Bennett, Silver, and Ashley (1963)

□ T = room temp (fresh deposited)
○ T = room (aged in air for several weeks)
} 10^{-5} mm Hg deposition } Bennett, Bennett, and Ashley (1962)

TABLE 2.2 SPECTRAL REFLECTANCE OF ANTIMONY

Reflectance λ, μ	Reflectance $\rho_{\lambda,0}$ (T = 2.5°K)	Sample Preparation	Radation Source	Method	Reference
		Cast sample--mechanically polished. Composition: Sb = 99.7%, Ca = .02%, Mg = .01%	Monochromatic	3(a)*	Potapov [1965]
1	0.6771				
2	0.6488				
3	0.6321				
4	0.6171				
5	0.6132				
6	0.6154				
7	0.6108				
8	0.6082				
9	0.5963				
10	0.6696				
11	0.7647				
12	0.8154				
(See figure 2.2 for $\rho_{\lambda,0}$.) (T = 110°K and 290°K)		Vacuum precipitation on silver plated glass surface.	Monochromatic	3(b)	Shklyarevskii, Avdeenko, and Padalka [1959]

*Direct measurement of $\rho_{\lambda,0}$, using normal incidence of light, was used by Potapov [1965] to check $\rho_{\lambda,0}$ values calculated from optical constants. Excellent agreement was obtained.

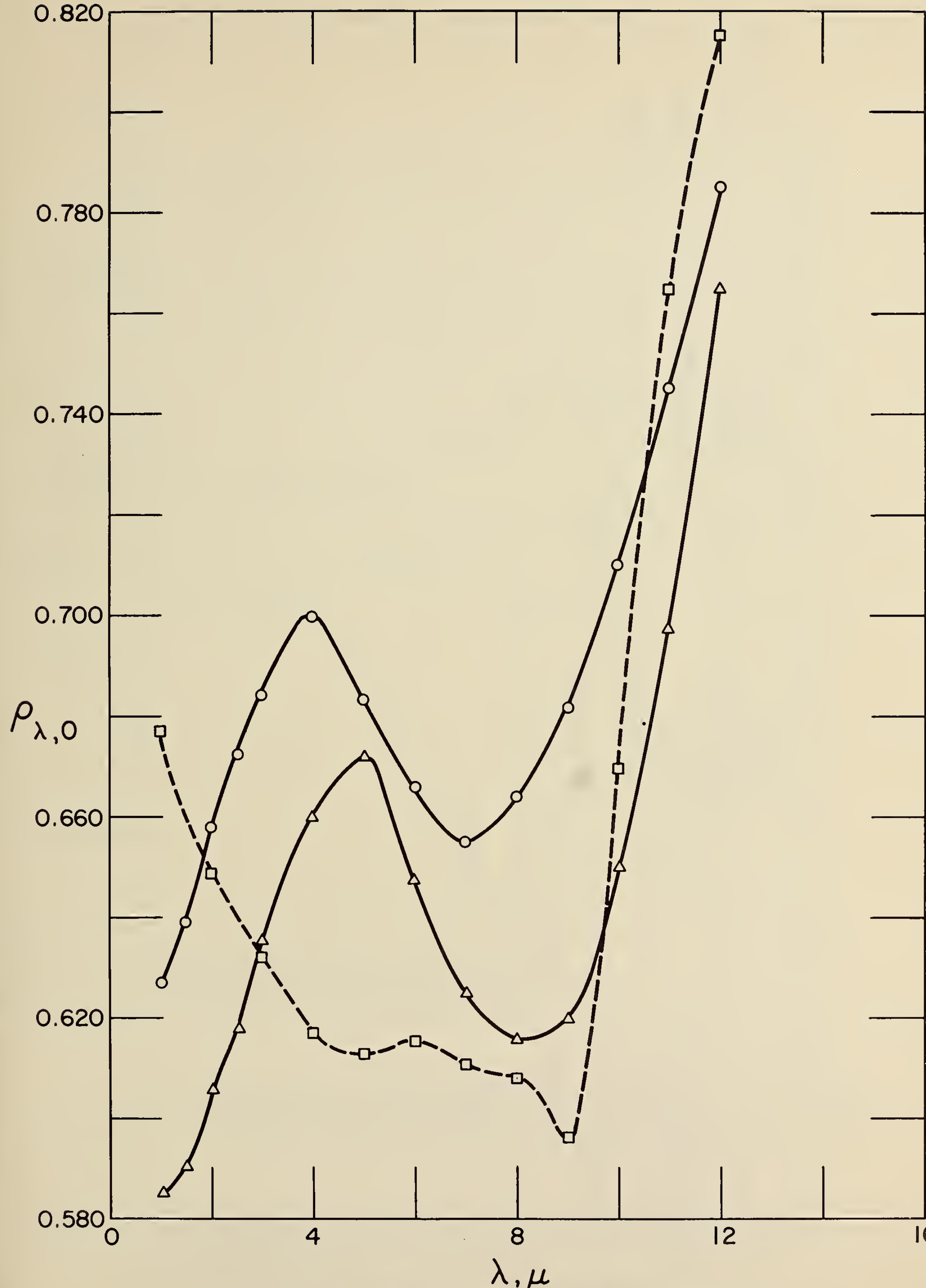

Figure 2.2 Spectral reflectance of antimony

○ T = 110°K ⎫ Shklyarevskii, Avdeenko,
△ T = 290°K ⎭ and Padalka (1959)

□ T = 2.5°K Potapov (1965)

TABLE 2.3 SPECTRAL REFLECTANCE OF BISMUTH AND BISMUTH-TELLURIUM ALLOYS

Reflectance				Sample Preparation	Radiation Source	Method	Reference
Bismuth and Bismuth-Tellurium Alloys				Electropolished (Spectroscopically pure "Hilger" bismuth) (.05% and .5% Te added to pure Bi)	Monochromatic	3(a)	Potapov [1965]
λ, μ	$\rho_{\lambda,0}$ at 2.5°K						
	Bi	Bi + .5% Te	Bi + .05% Te				
1	0.6260	0.5266	0.5388				
2	0.5842	0.5249	0.5408				
3	0.5902	0.5193	0.5405				
4	0.5963	0.5240	0.5426				
5	0.5902	0.5098	0.5375				
6	0.5968	0.4720	0.5465				
7	0.6085	0.4214	0.5425				
8	0.6145	0.3757	0.5343				
9	0.6358	0.3464	0.5303				
10	0.6547	0.4570	0.5240				
11	0.6377	0.6444	0.5016				
12	0.6340	0.7924	0.4457				
13	0.6440	--	0.3977				
14	--	--	0.4371				

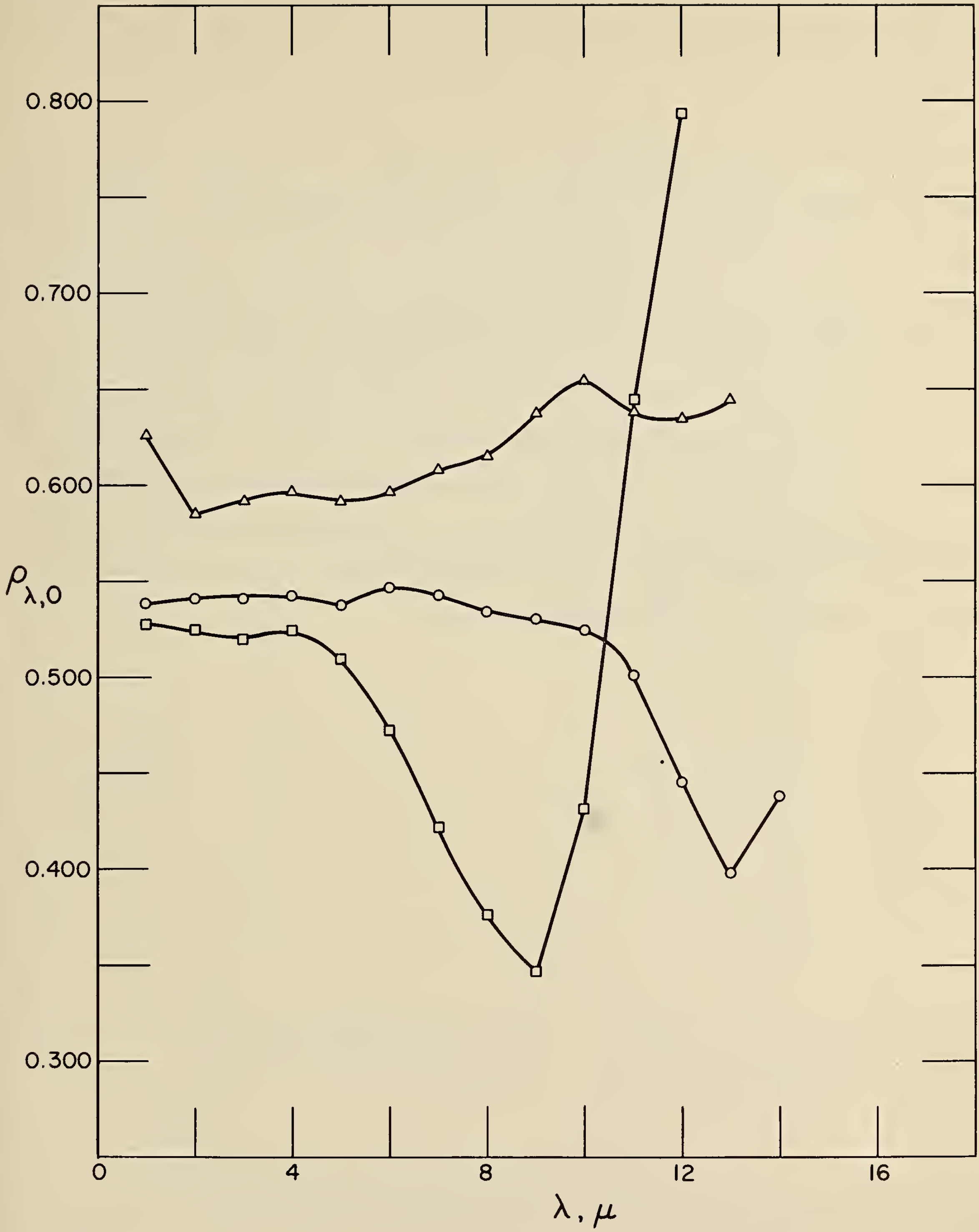

Figure 2. 3 Spectral reflectance of bismuth and bismuth-tellurium alloys

△ Bismuth
○ Bismuth + .05% Te
□ Bismuth + .5 % Te
} T = 2.5°K Potapov (1965)

2.4 Copper

Results of Roberts [1960], Biondi[1956], and Rayne [1959] for electropolished samples are seen to have significantly higher reflectances than those of Padalka and Shklyarevskii [1962] for high-vacuum deposited samples (fig. 2.4). Variations with temperature for a given preparation technique follow expectations. A correction for an oxide layer of 35-Å thickness was carried out by Padalka and Shklyarevskii [1962]. Although a significant effect on refractive index and absorption coefficient was found, the effect on reflectance was less than 0.2% at 1 μ and .005% at 11 μ (present authors' calculations). The 35-Å thickness correction followed Roberts' [1960] results which showed a 30-Å to 40-Å equilibrium oxide layer thickness after exposure to air.

TABLE 2.4 SPECTRAL REFLECTANCE OF COPPER

Reflectance			Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda, 0}$		Vacuum deposition at 10^{-5} mm Hg. Sample impurities $< 10^{-3}$%	Monochromatic	3(b)	Padalka and Shklyarevskii [1962]
	T = 82°K	T = 295°K				
1	.9571	.9530				
2	.9833	.9808				
3	.9885	.9860				
4	.9902	.9879				
5	.9911	.9888				
6	.9916	.9892				
7	.9919	.9894				
8	.9921	.9896				
9	.9923	.9899				
10	.9924	.9901				
11	.9926	.9903				
λ, μ	$\rho_{\lambda, 0}$		Electropolished and reduced in vacuum (2×10^{-5} mm Hg). at 500°K to remove oxide film. Sample purity > 99.999%	Monochromatic	3(b)	Roberts [1960]
	90°K	300°K				
0.3650	0.5162	0.5003				
0.4050	0.5567	0.5490				
0.4360	0.5935	0.5859				
0.5000	0.6514	0.6527				
0.5500	0.6872	0.7012				
0.5780	0.9119	0.8715				
0.6000	0.9682	0.9508				
0.6500	0.9811	0.9740				
0.7500	0.9873	0.9835				
1.0000	0.9914	0.9881				
1.5000	0.9935	0.9908				
2.0000	0.9941	0.9917				
2.5000	0.9944	0.9920				

TABLE 2.4 SPECTRAL REFLECTANCE OF COPPER (continued)

Reflectance	Sample Preparation	Radiation Source	Method	Reference
$\rho_0 = 1 - \alpha_0 = 0.9956$ (limiting value for $T < 100°K$) (See figure 2.4.)	Electropolished	Frequency band from $1.8\,\mu$ to $4.0\,\mu$	2	Rayne [1959]
$\rho_{\lambda,0} = 0.995$ (limiting value for $\lambda > 1.5\,\mu$) ($T = 4.2°K$) (See figure 2.4.)	Electropolished Purity > 99.999%	Monochromatic	2	Biondi [1956]

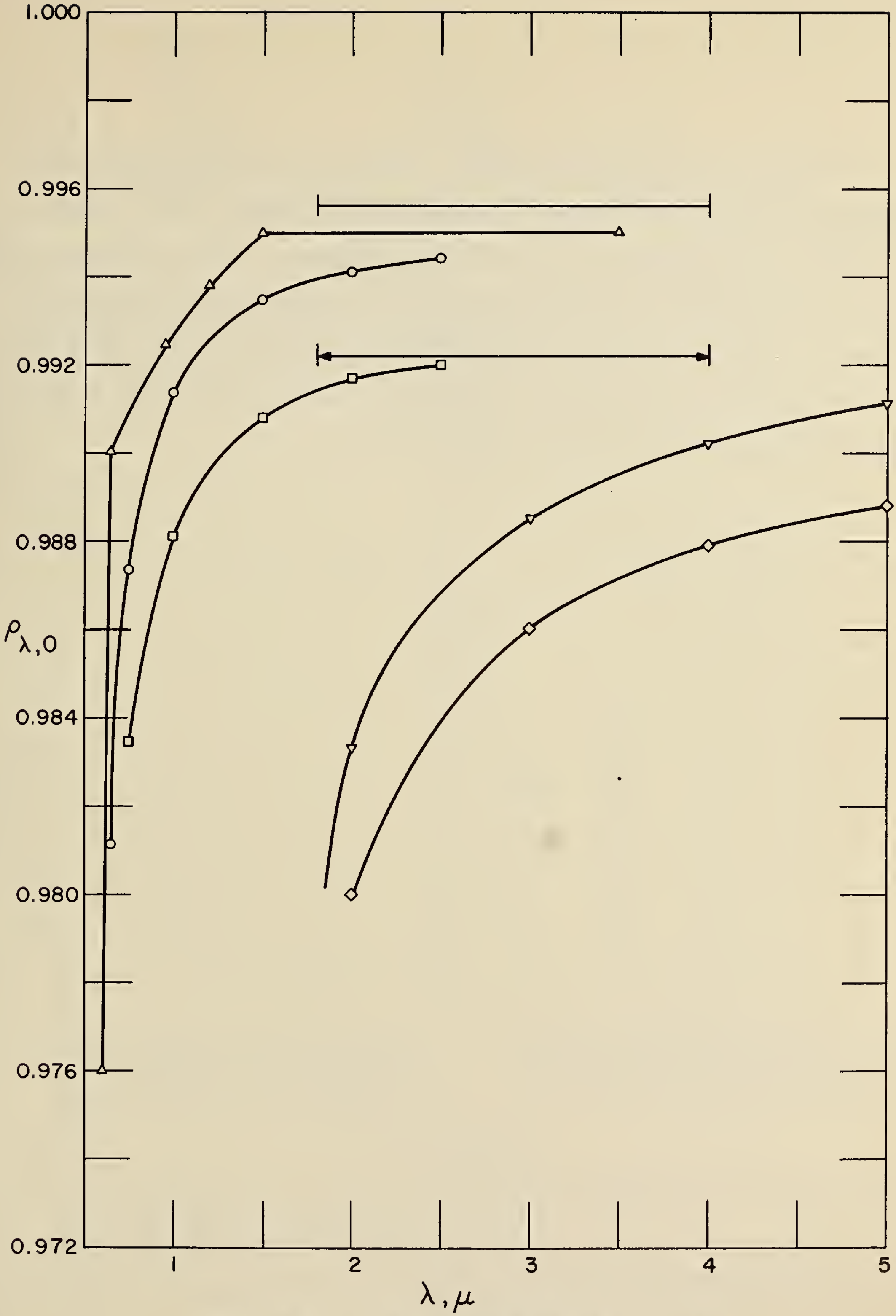

Figure 2.4 Spectral reflectance of copper

○ T = 90°K, □ T = 300°K — Roberts (1960)

△ T = 4.2°K — Biondi (1956)

▽ T = 82°K, ◇ T = 295°K — Padalka and Shklyarevskii (1962)

⊢⊣ T < 100°K, ⊢⊣ T = 100°K — Rayne (1959) Frequency band: λ = 1.8 to 4 μ

2.5 Gold

In view of the high reflectance values of gold obtained in the infrared at room temperature by Bennett and Ashley [1965] using ultra-high-vacuum deposition, it would be interesting to make these measurements at cryogenic temperatures using the same sample preparation technique. Such a result would be extremely useful in view of the potential use of gold as a standard of reflectance and in view of the wide application of gold plating in dewar construction.

TABLE 2.5 SPECTRAL REFLECTANCE OF GOLD

Reflectance			Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda,0}$ 82°K	$\rho_{\lambda,0}$ 295°K				
1	0.9658	0.9623	Vacuum deposition at 10^{-5}	Monochromatic	3(b)	Padalka
2	0.9859	0.9831	mm Hg.			and
3	0.9895	0.9868				Shklyarevskii
4	0.9908	0.9881	Purity > 99.99%			[1961]
5	0.9914	0.9887				
6	0.9917	0.9891				
7	0.9919	0.9894				
8	0.9922	0.9895				
9	0.9923	0.9897				
10	0.9924	0.9899				
11	0.9925	0.9900				

(Room temperature)				Sample Preparation	Radiation Source	Method	Reference
$\lambda(\mu)$	$\rho_{\lambda,0}$	$\lambda(\mu)$	$\rho_{\lambda,0}$				
0.575	0.8708	9	0.9939	Ultra-high vacuum deposition	Monochromatic	1	Bennett
0.600	0.9116	10	0.9939	at 10^{-9} mm Hg.			and
0.650	0.9566	11	0.9940				Ashley
0.700	0.9695	12	0.9940	Purity > 99.999+ %			[1965]
0.800	0.9795	13	0.9940				
0.900	0.9839	14	0.9940				
1.000	0.9860	16	0.9940				
1.200	0.9878	18	0.9940				
1.500	0.9896	20	0.9940				
2.000	0.9914	22	0.9941				
3.000	0.9930	24	0.9941				
4.000	0.9938	26	0.9941				
5.000	0.9938	28	0.9941				
6.000	0.9939	30	0.9942				
7.000	0.9939	32	0.9942				
8.000	0.9939						

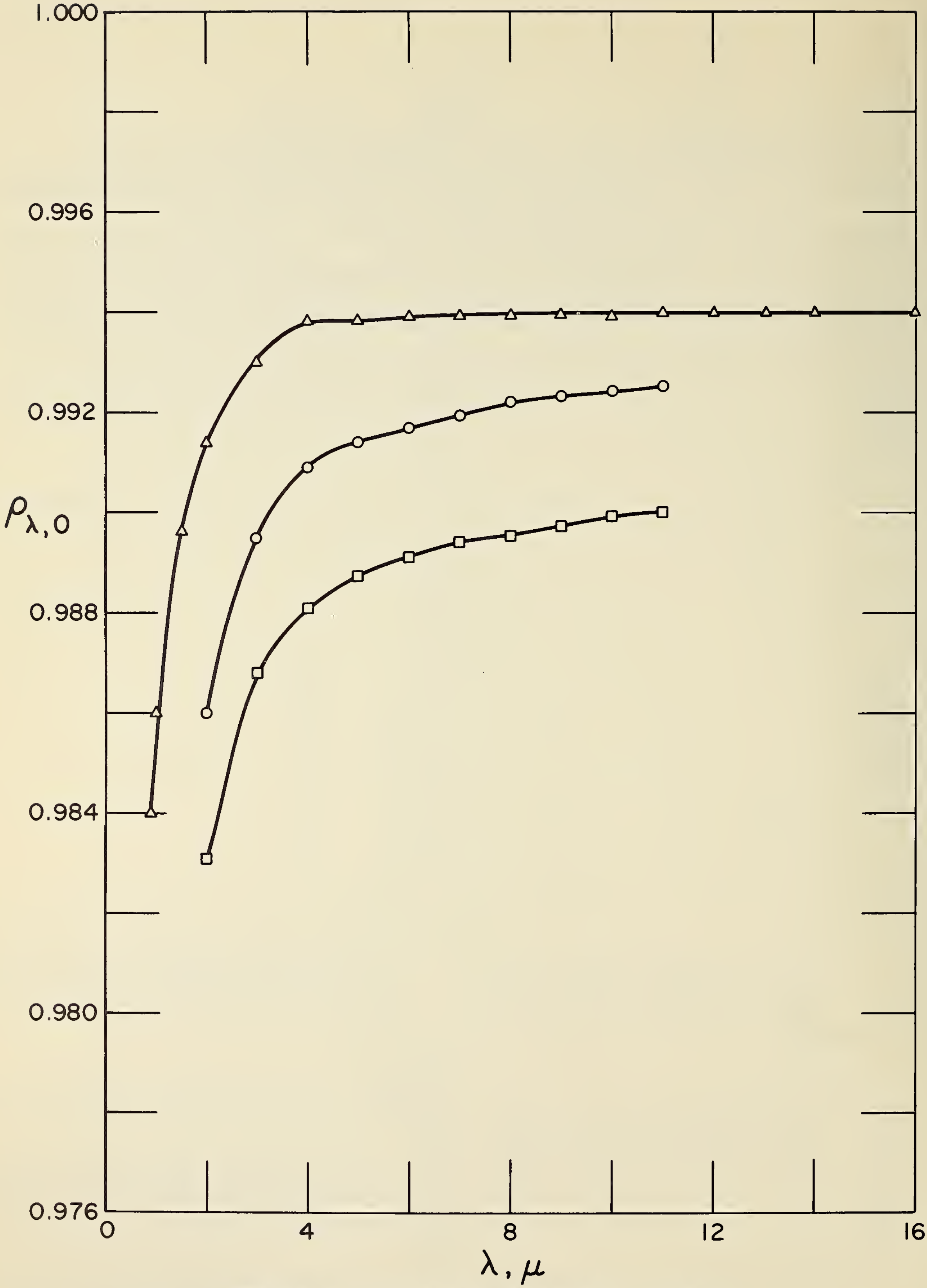

Figure 2.5 Spectral reflectance of gold

△ T = room temperature (10^{-9} mm Hg deposited) Bennett and Ashley (1965)

○ T = 82°K
□ T = 295°K } (10^{-5} mm Hg deposited) Padalka and Shklyarevskii (1961)

2.6 Lead

Measurements of optical constants of lead made by Golovashkin [1965] immediately after deposition and after several days in vacuum gave identical results. No effect of oxidation on results was found after one day in air; although, after several days in air, noticeable changes in optical constants (of unstated magnitude) were observed by the original author.

TABLE 2.6 SPECTRAL REFLECTANCE OF LEAD

Reflectance				Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda, 0}$ 4°K	$\rho_{\lambda, 0}$ 78°K	$\rho_{\lambda, 0}$ 293°K				
0.7	--	--	0.6746	Vacuum deposition at $5 - 8 \times 10^{-6}$ mm Hg. Purity >99.999+ %	Monochromatic	3(b)	Golovashkin [1965]
0.8	--	0.7836	0.7512				
0.9	0.8511	0.8392	0.8046				
1.0	0.9001	0.8829	0.8387				
1.1	0.9315	0.9093	0.8631				
1.2	0.9547	0.9361	0.8801				
1.3	0.9721	0.9515	0.8940				
1.4	0.9809	0.9614	0.9030				
1.5	0.9843	0.9671	0.9110				
1.7	0.9874	0.9728	0.9210				
2.0	0.9899	0.9766	0.9319				
2.5	0.9898	0.9791	0.9377				
3.0	0.9893	0.9800	0.9424				
3.5	0.9892	0.9811	0.9443				
4.0	0.9890	0.9815	0.9463				
5.0	0.9896	0.9812	0.9495				
6.0	0.9902	0.9818	0.9508				
7.0	0.9907	0.9817	0.9523				
8.0	0.9914	0.9826	0.9542				
9.0	0.9915	0.9835	0.9552				
10.0	0.9916	0.9843	0.9554				
11.0	0.9918	0.9846	0.9563				
12.0	0.9919	0.9849	0.9571				

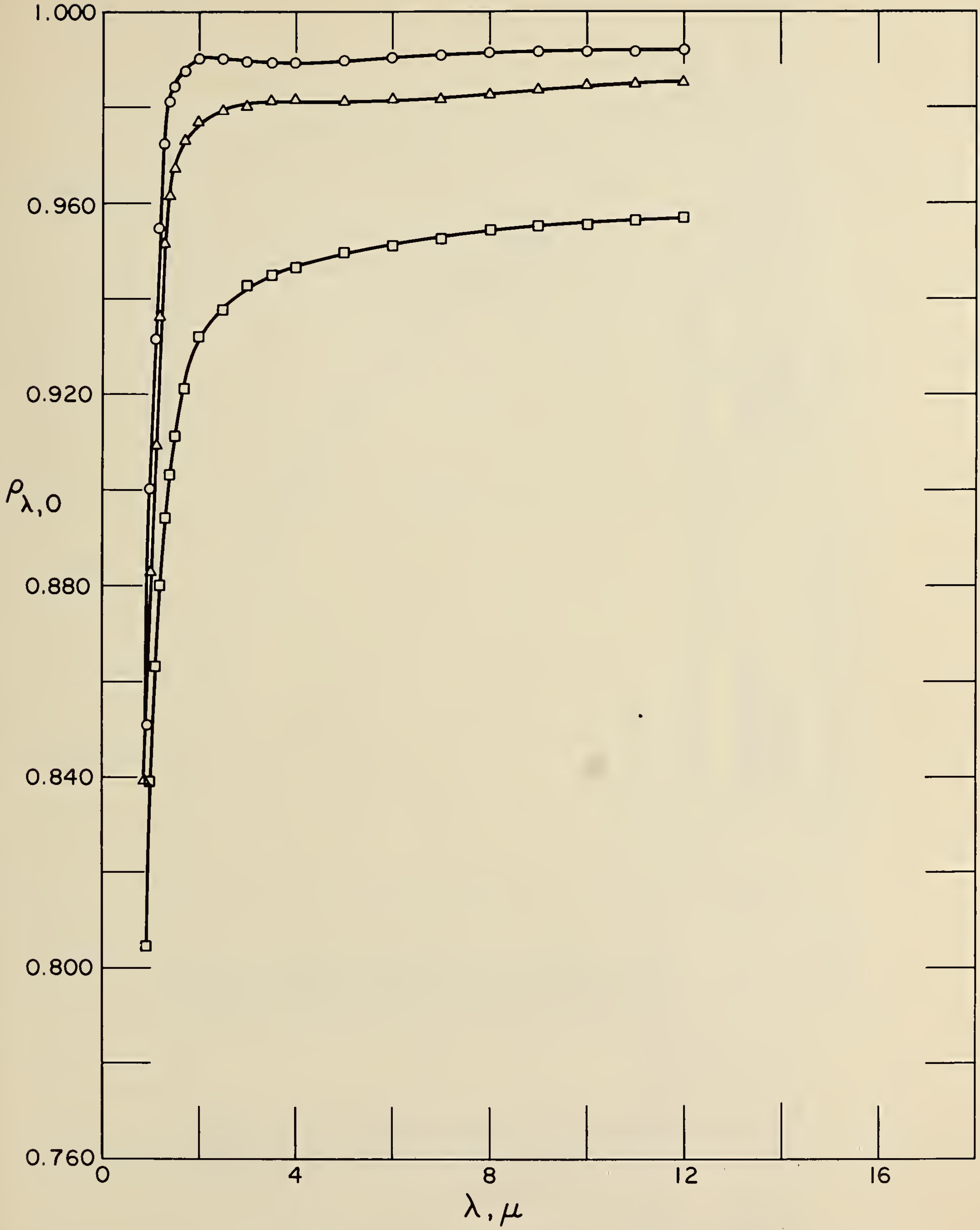

Figure 2.6 Spectral reflectance of lead

○ T = 4°K
△ T = 78°K
□ T = 293°K

} Golovashkin (1965)

TABLE 2.7 SPECTRAL REFLECTANCE OF NICKEL

Reflectance			Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda,0}$		Electropolished nickel bar of 99.98% purity.	Monochromatic	3(b)	Roberts [1959]
	T = 88°K	298°K				
0.365	0.4766	0.4882				
0.436	0.5708	0.5739				
0.546	0.6452	0.6444				
0.60	0.6711	0.6678				
0.65	0.6886	0.6865				
0.75	0.7089	0.7068				
0.85	0.7195	0.7209				
1.00	0.7429	0.7433				
1.10	0.7585	0.7602				
1.25	0.7818	0.7827				
1.50	0.8135	0.8128				
1.75	0.8357	0.8377				
1.95	0.8507	0.8494				
2.20	0.8685	0.8651				
2.40	0.8826	0.8770				
2.65	0.8954	0.8899				

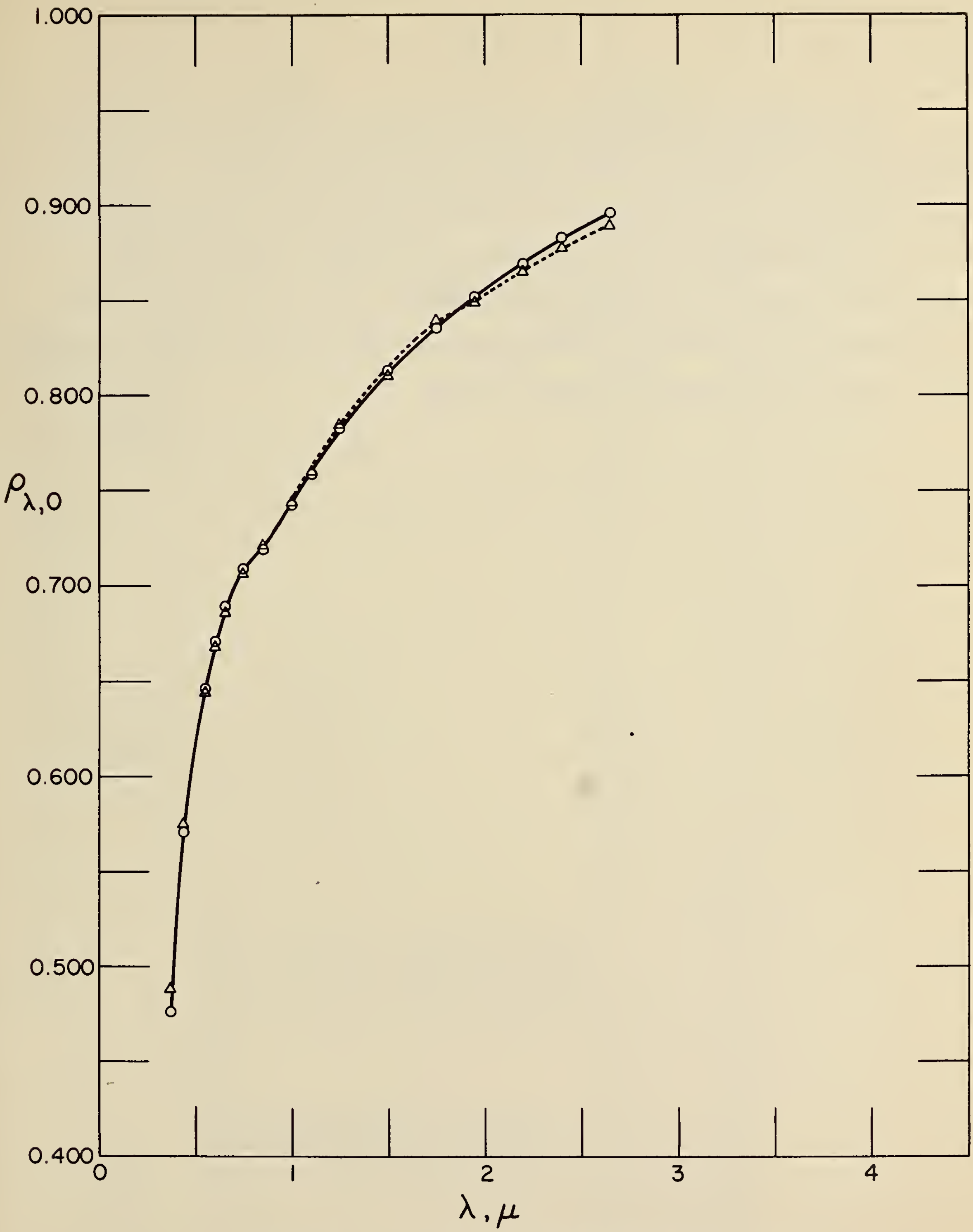

Figure 2.7 Spectral reflectance of nickel

○ T = 88°K
△ T = 298°K
} Roberts (1959)

2.8 Silver

Ultra-high-vacuum deposited silver is seen in figure 2.8 to have a reflectance significantly higher than that of a film deposited using the usual high-vacuum techniques. It is noteworthy that Biondi's results for electropolished samples at 4.2°K show even higher reflectance than ultra-high-vacuum room temperature values. As in the case of gold, the reflectance at cryogenic temperatures of ultra-high-vacuum deposited silver would be an extremely useful result.

TABLE 2.8 SPECTRAL REFLECTANCE OF SILVER

Reflectance			Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda,0}$ T = 82°K	$\rho_{\lambda,0}$ T = 295°K				
1	0.9816	0.9791	Vacuum deposition at 10^{-5} mm of Hg.	Monochromatic	3(b)	Padalka and Shklyarevskii [1961]
2	0.9878	0.9855				
3	0.9891	0.9868	Purity > 99.99%			
4	0.9895	0.9873				
5	0.9899	0.9875				
6	0.9901	0.9877				
7	0.9902	0.9880				
8	0.9903	0.9882				
9	0.9905	0.9885				
10	0.9907	0.9887				
11	0.9909	0.9890				
12		0.9893				
$\rho_{\lambda,0}$ = 0.9956 (limiting value for $\lambda > 1.5\,\mu$) (T = 4.2°K)(See figure 2.8)			Electropolished	Monochromatic	2	Biondi [1956]

TABLE 2.8 SPECTRAL REFLECTANCE OF SILVER (continued)

Reflectance				Sample Preparation	Radiation Source	Method	Reference
(Room temperature)				Ultra-high vacuum deposition	Monochromatic	1	Bennett
$\lambda(\mu)$	$\rho_{\lambda,0}$	$\lambda(\mu)$	$\rho_{\lambda,0}$	at 10^{-9} mm Hg.			and
0.400	0.9564	7	0.9950				
0.450	0.9706	8	0.9951				Ashley
0.500	0.9786	9	0.9952				
0.550	0.9831	10	0.9953	Purity > 99.999+ %			[1965]
0.600	0.9860	11	0.9954				
0.650	0.9880	12	0.9954				
0.700	0.9894	13	0.9955				
0.800	0.9916	14	0.9955				
0.900	0.9929	16	0.9956				
1.000	0.9936	18	0.9956				
1.200	0.9938	20	0.9956				
1.500	0.9939	22	0.9956				
2.000	0.9940	24	0.9957				
3.000	0.9942	26	0.9957				
4.000	0.9944	28	0.9958				
5.000	0.9946	30	0.9958				
6.000	0.9948	32	0.9958				

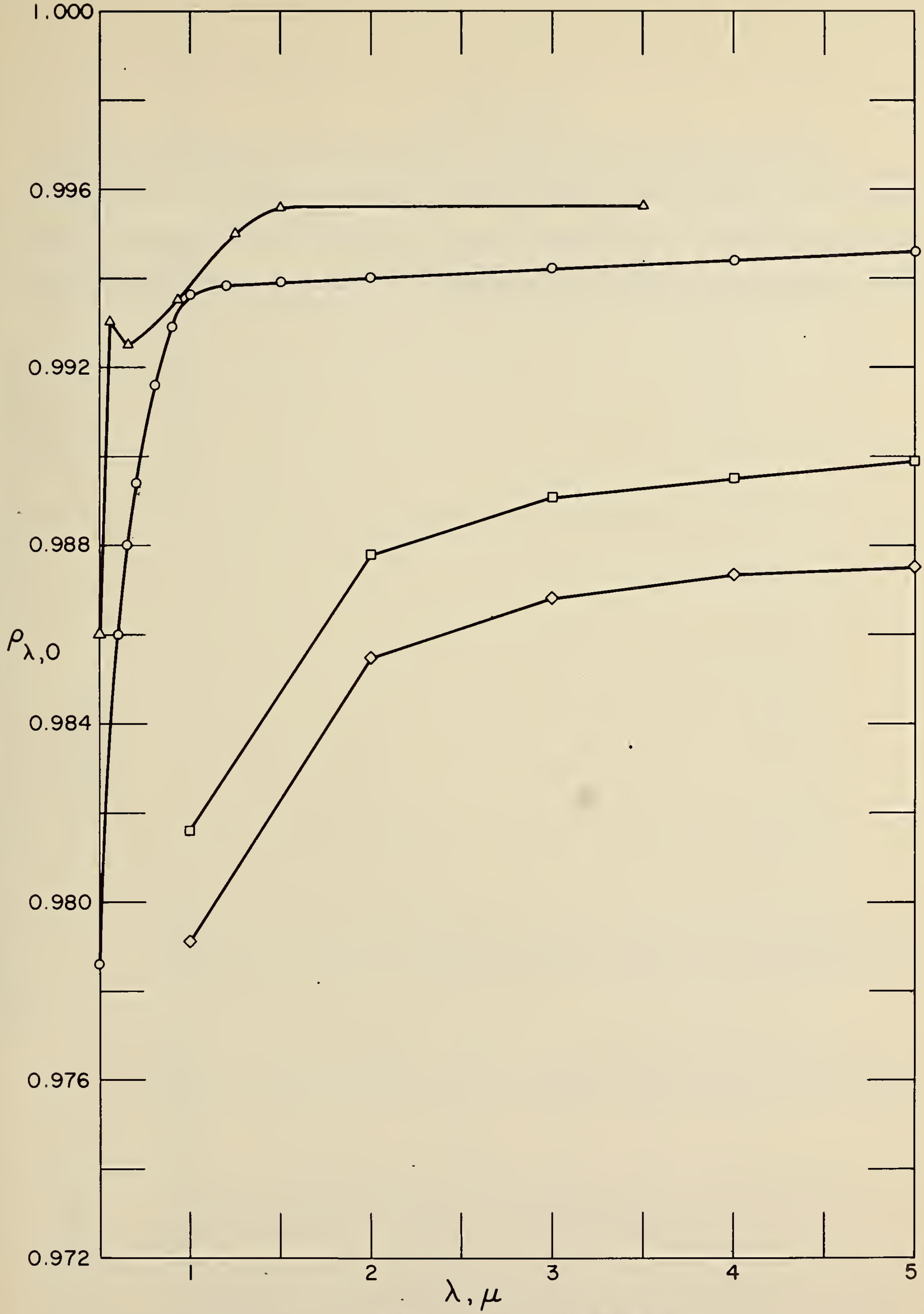

Figure 2.8 Spectral reflectance of silver

△ T = 4.2°K Biondi (1956)

○ T = room temp Bennett and Ashley (1965)

□ T = 82°K } Padalka and

◇ T = 295°K } Shklyarevskii [196

2.9 Sodium

At the time this publication went to press, additional work of Mayer and Hietel [1966] on the alkali metals, potassium and cesium, became available. Wavelength range investigated was essentially that here reported for sodium. For details, consult the original reference.

TABLE 2.9 SPECTRAL REFLECTANCE OF SODIUM

Reflectance				Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda,0}$ 90°K	$\rho_{\lambda,0}$ 195°K	$\rho_{\lambda,0}$ 293°K		Monochromatic	3(b)	Hietel [1965]
0.2968	0.905	0.912	0.924				
0.3126	0.902	--	0.909				
0.3342	0.907	0.921	0.905				
0.3655	0.904	0.910	0.910				
0.4047	0.908	0.924	0.930				
0.4348	0.920	0.932	0.944				
0.4916	0.939	0.945	0.957				
0.5460	0.960	0.965	0.974				
0.6000	0.983	0.975	0.968				
0.6500	0.990	--	0.970				
0.7000	0.995	0.986	0.974				
0.7500	0.995	--	0.976				
0.8000	0.997	0.990	0.981				
0.9000	0.999	0.993	0.989				
1.0000	0.999	0.995	0.992				
1.1000	0.997	0.995	0.993				
1.2000	0.998	0.995	0.993				
1.3000	0.997	0.995	0.993				
1.4000	0.998	0.995	0.993				
1.5000	0.998	0.996	0.993				
1.6000	0.998	0.996	0.993				
1.7000	0.998	0.996	0.993				
1.8000	0.998	0.996	0.993				
1.9000	0.998	0.995	0.993				
2.0000	0.998	0.996	0.993				
2.1000	--	0.996	0.993				
2.2000	0.998	0.996	0.993				
2.3000	--	0.995	0.993				
2.4000	--	0.995	0.993				
2.5000	--	0.995	0.993				

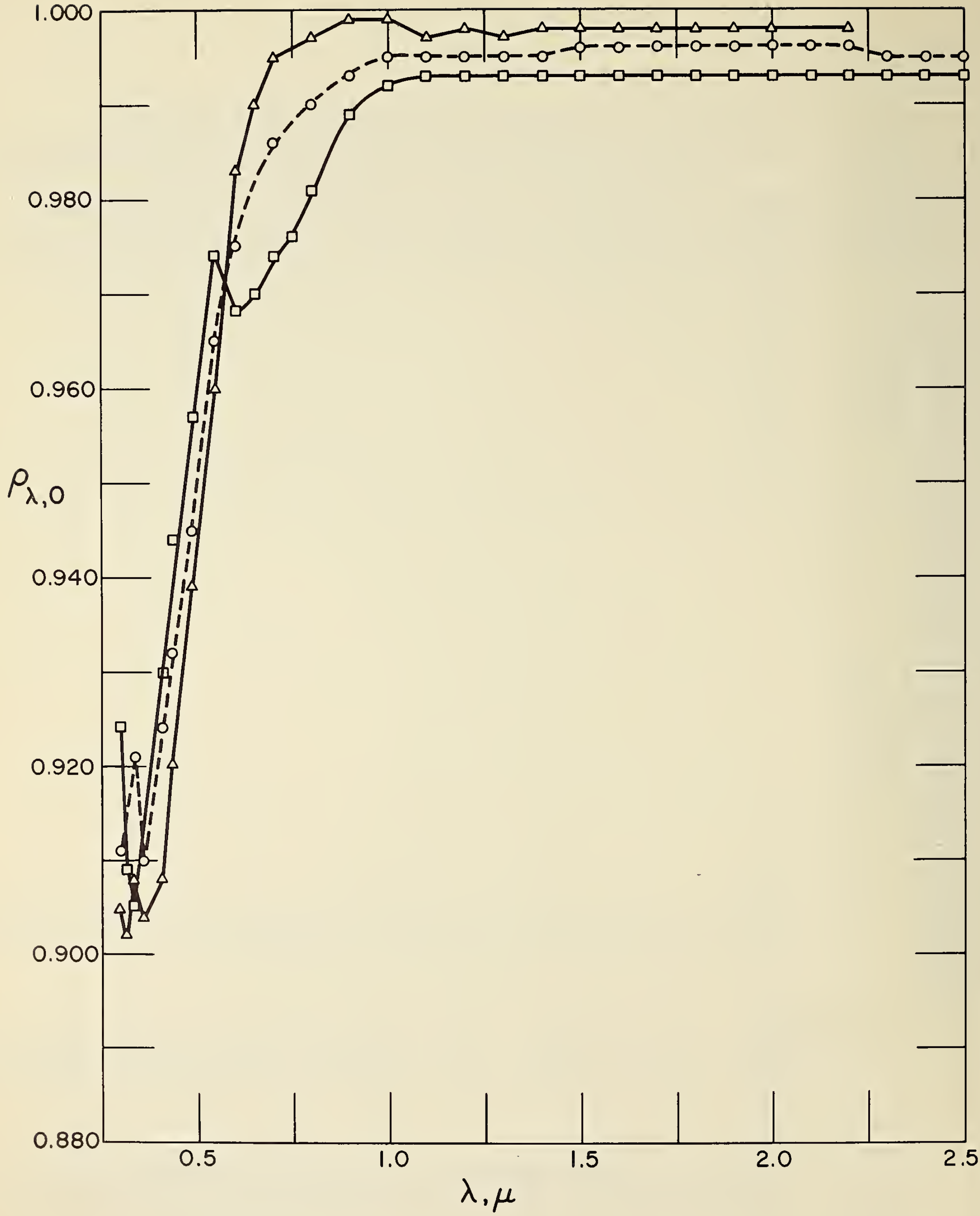

Figure 2.9 Spectral reflectance of sodium

△ T = 90°K
○ T = 195°K } Hietel (1965)
□ T = 293°K

2.10 Tin

Optical constants of tin were measured by Golovashkin and Motulevich [1965] immediately after vapor deposition and after one day in vacuum with identical results. After a 48-hour exposure to atmosphere, the change in n was 2 to 3% and $k < 1\%$. This variation in optical constants affected the reflectance by less than 0.002% for $\lambda > 5\,\mu$ (present authors' calculation).

TABLE 2.10 SPECTRAL REFLECTANCE OF TIN

Reflectance				Sample Preparation	Radiation Source	Method	Reference
λ, μ	$\rho_{\lambda,0}$ 4.2°K	78°K	293°K				
.93	.8398	.8068	.8205	Vacuum deposition at	Monochromatic	3(b)	Golovashkin
.99	.7978	.7833	.8130	$5 - 8 \times 10^{-6}$ mm Hg.			and
1.2	.7661	.7727	.8140				Motulevich
1.35	.8200	.8247	.8330				[1965]
1.5	.8859	.8858	.8587	Purity >99.99%			
1.7	.9355	.9254	.8908				
2.0	.9592	.9518	.9205				
2.5	.9745	.9693	.9396				
3.0	.9808	.9773	.9490				
3.5	.9828	.9812	.9541				
4.0	.9856	.9835	.9580				
5.0	.9879	.9834	.9623				
6.0	.9885	.9846	.9645				
7.0	.9889	.9852	.9654				
8.0	.9894	.9857	.9660				
9.0	.9891	.9856	.9668				
10.0	.9886	.9849	.9671				
11.0	.9880	.9837	.9676				
12.0	.9871	.9836	.9681				

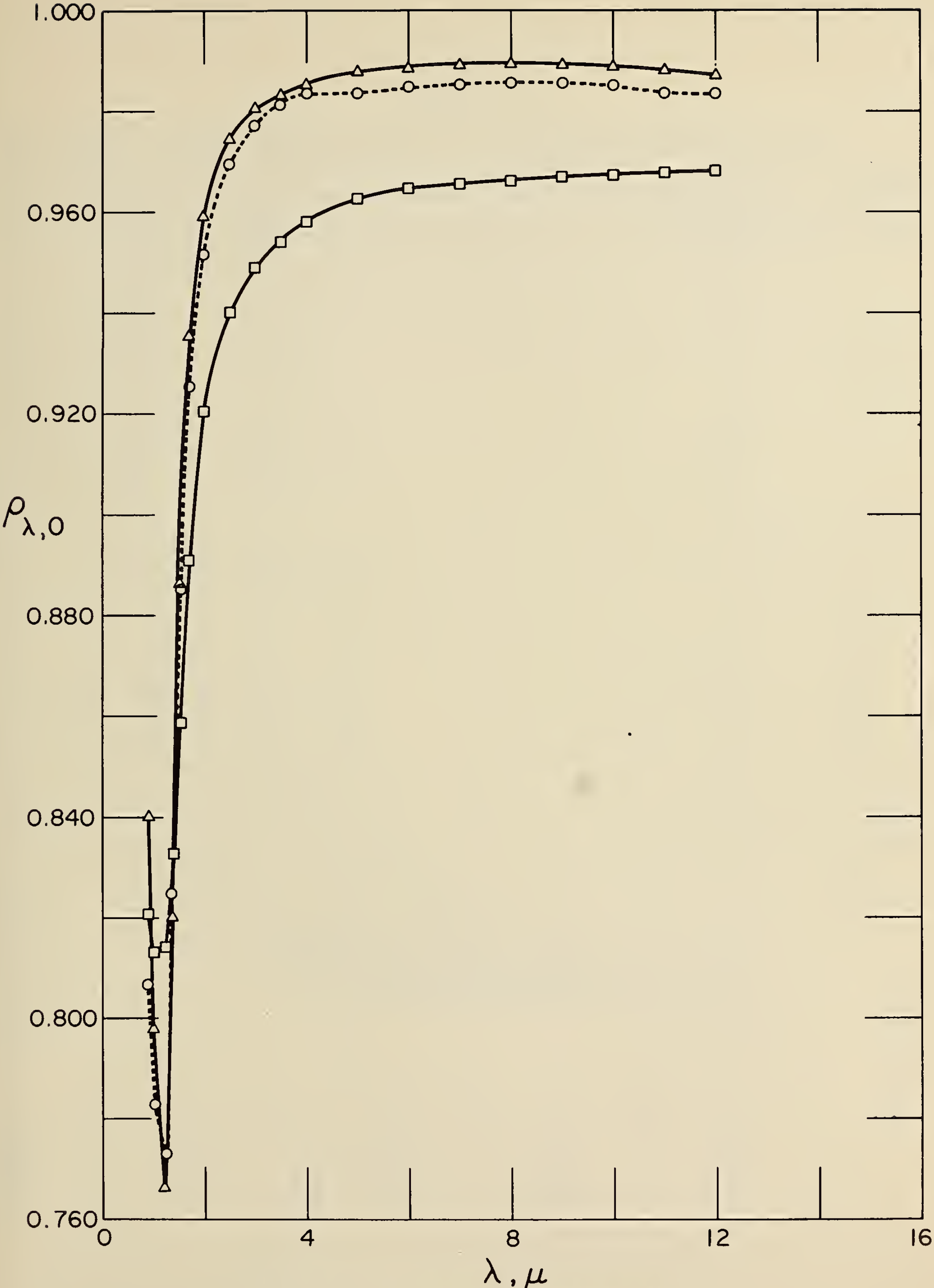

Figure 2. 10 Spectral reflectance of tin

△ T = 4. 2°K
○ T = 78°K
□ T = 293°K

Golovashkin and Motulevich (1965)

2.11 Brass

Results of spectral reflectance measurements on various electro-polished α-brasses at 4.2°K by Biondi and Rayne [1959] using Method 2 are presented in figure 2.11 compared with pure copper.

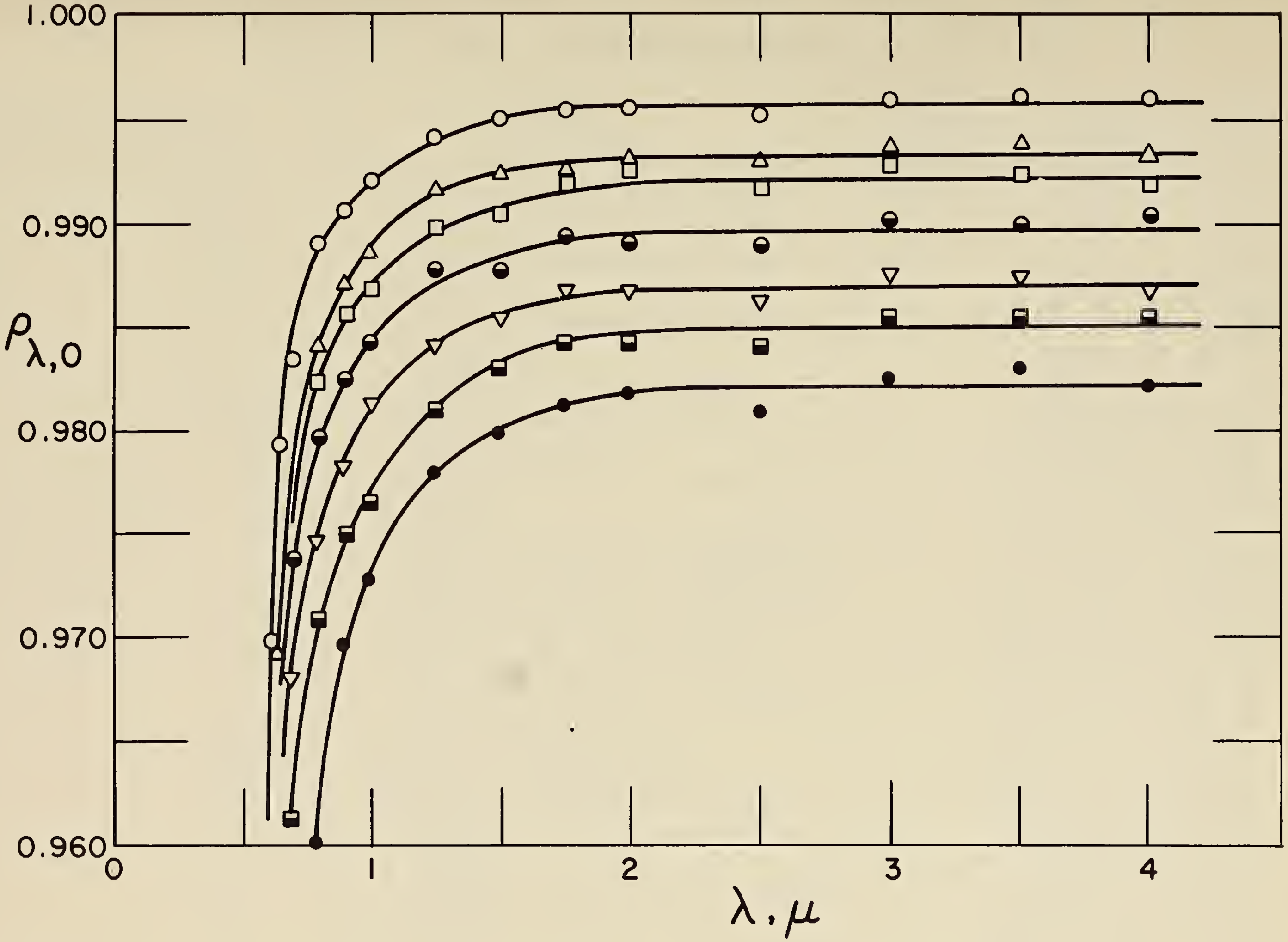

Figure 2.11 Spectral reflectance of α-brasses

Biondi and Rayne (1959) ○ Copper △ 2 1/2% Zinc □ 5% Zinc ◒ 10% Zinc ▽ 15% Zinc ▣ 20% Zinc ● 30% Zinc

3. Total Reflectance

Until recently, nearly all the reflectance data reported in the literature were total normal reflectance ($\rho_{t,0}$) or total hemispherical reflectance (ρ_t). For this reason, many of the results below have been presented in previous surveys but are given here for completeness. Results of Betz, Olson, Schurin, and Morris [1958] are for total normal emittance ($\epsilon_{t,0}$) and are reported as such.

TABLE 3.1 TOTAL REFLECTANCE OF ALUMINUM

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
$\rho_t = 0.982$	0.001 in. Kaiser foil unannealed	Source at	4	Fulk and
0.982	0.0015 in. Cockron home foil			
0.979	0.0015 in. Hurwich home foil--mat side	300°K		Reynolds
(T = 76°K) 0.978	0.0015 in. Hurwich home foil--bright side			[1957b]
0.972	0.020 in. cold acid cleaned			
0.971	0.020 in. hot acid cleaned, Alcoa process			
0.974	0.020 in. Alcoa No. 2 reflector plate			
0.968	0.020 in. Alcoa No. 2 reflector plate sanded with fine emery			
0.965	0.020 in. Alcoa No. 2 reflector plate cleaned with alkali			
0.955	0.020 in. wire brush, emery paper, steel wool, cold acid			
0.94	0.020 in. wire brush			
0.986	0.020 in. Liquid honed			
0.96	Aluminum vaporized onto both sides of 0.0005 in. plastic Mylar			
0.93	Aluminum sprayed onto stainless steel			
0.94	Aluminum sprayed onto stainless steel and wire brushed			

TABLE 3.1 TOTAL REFLECTANCE OF ALUMINUM (continued)

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
$\rho_t = 0.957$ (T = 77°K)	Foil	Source at 273°K	4	Ziegler and Cheung [1956]
$\rho_{t,0} = 0.9889$ (T = 2.0 to 4.2°K)	Electropolished Sample impurities < .01%	Source at room temperature ($\lambda_{mean} \approx 14\mu$)	2	Ramanathan [1952]
$\rho_t = 0.945$ (T = 90°K)	Foil (dry buffed)	Source at 293°K	4	Blackman, Egerton, and Truten [1948]
Aluminum Alloy 24-ST $\epsilon_{t,0}$ T = 83.3°K / T = 422.2°K 0.011 / 0.004 0.022 / 0.006 0.022 / 0.006 0.022 / 0.044	 as received from the supplier. cleaned with a liquid detergent. polished mechanically. oxidized in air at red heat for 30 minutes	--	5	Betz, Olson, Schurin, and Morris [1958]

TABLE 3.2 TOTAL REFLECTANCE OF COPPER

Reflectance or Emittance		Sample Preparation	Radiation Source	Method	Reference
$\epsilon_{t,0}$					
T = 83.3°K	T = 422.2°K				
0.066	--	Electrolytic copper, Federal Specification QQ-C-576 or QQ-C-502. as received from supplier.	--	5	Betz, Olson, Schurin, and Morris [1958]
0.005	--	cleaned with liquid detergent.			
0.025	--	mechanically polished.			
0.065	0.165	oxidized in air at red heat for 30 min.			
ρ_t = 0.985		0.005 in. Millrun sheet (annealed)	Source at 300°K	4	Fulk and Reynolds (1957b)
0.983		0.005 in. dilute chromic acid dip			
0.982		0.005 in. wet polished with pumice			
0.981	(T = 76°K)	0.005 in. dry polished with plastic polishing wax abrasive			
0.983		0.005 in. electrolytically cleaned			
0.912		0.020 in. liquid honed			
0.977		0.005 in. fine emery			
0.97		Commercial copper sphere-- polished			
0.97		Commercial copper sphere-- Oakite No. 33 cleaned			
0.99		Commercial copper sphere-- Alleghany silver spray coated			
0.98		Commercial copper sphere-- tinned			

TABLE 3.2 TOTAL REFLECTANCE OF COPPER (continued)

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
$\rho_t = 0.985$ $(T = 77.3°K)$	Polished copper (solid copper sheet)	Source at 300°K	4	Zimmerman [1955]
(1) $\rho_{t,0} = 0.9938$ (2) $\rho_{t,0} = 0.9853$ $(T = 2.0$ to $4.2°K)$	(1) Electropolished (2) Mechanically polished	Source at room temperature $(\lambda_{mean} \approx 14\mu)$	2	Ramanathan [1952]
$\rho_t = 0.992$ $(T = 90°K)$	Pure copper (carefully prepared)	Frequency band: $\lambda = 2$ to $18\ \mu$	2	Weiss [1948]
(1) $\rho_t = 0.981$ (2) $= 0.968$ (3) $= 0.965$ $(T = 90°K)$	(1) Polished (reduced) (2) Matt (reduced) (3) Polished	Source at 293°K	4	Blackman, Egerton and Truten [1948]

TABLE 3.3 TOTAL REFLECTANCE OF GOLD

Reflectance	Sample Preparation	Radiation Source	Method	Reference
(T = 76°K)		Source at 300°K	4	Fulk and Reynolds [1957b]
(1) $\rho_t = 0.990$	Gold - 0.0015 in. Foil			
(2) $\rho_t = 0.984$	0.0005 in. Foil			
(3) $\rho_t = 0.977$	0.000040 in. Foil			
(4) $\rho_t = 0.938$	0.00001 in. Leaf			
(5) $\rho_t = 0.975$	Gold plate - 0.0002 in. on stainless steel 1% silver in gold			
(6) $\rho_t = 0.973$	0.0001 in. on stainless steel 1% silver in gold			
(7) $\rho_t = 0.972$	0.00005 in. on stainless steel 1% silver in gold			
(8) $\rho_t = 0.975$	0.0002 in. on copper, 1% silver in gold			
(9) $\rho_t = 0.983$	24K gold plate on stainless steel			
(10) $\rho_t = 0.980$	Gold vaporized onto both sides of 0.0005 in. Mylar plastic			
(T = 77.3°K)		Source at 300°K	4	Zimmerman [1955]
(1) $\rho_t = 0.986$	(1) Electroplated (unbuffed)			
(2) $\rho_t = 0.985$	(2) Gold wash			
(3) $\rho_t = 0.984$	(3) Dry buffed			
(4) $\rho_t = 0.982$	(4) Polished (kerosene buff)			
$\rho_t = 0.974$ (T = 90°K)	Foil (equivalent to buffed surface)	Source at 293°K	4	Blackman, Egerton, and Truten [1948]

TABLE 3.4 TOTAL REFLECTANCE OF LEAD

Reflectance	Sample Preparation	Radiation Source	Method	Reference
$\rho_t = 0.964$ $(T = 76°K)$	0.004 inch foil (commercial sheet)	Source at 300°K	4	Fulk and Reynolds [1957b]
$\rho_{t,0} = 0.9885$ $(T = 2.0 \text{ to } 4.2°K)$	Electropolished Impurities < 0.005%	Black body at room temperature $(\lambda_{mean} \approx 14\mu)$	4	Ramanathan [1952]

TABLE 3.5 TOTAL REFLECTANCE OF NICKEL AND NICKEL ALLOYS

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
Nickel (1) $\rho_t = 0.978$ } $T = 76°K$ (2) $\rho_t = 0.967$ } (3) $\rho_t = 0.973$ $(T = 20°K)$	(1) .004 inch foil (2) Plated on copper. (3) Plated on copper.	Source at 300°K	4	Fulk and Reynolds [1957b]
Nickel $\epsilon_{t,0}$: T = 83.3°K / T = 422.2°K 0.153 / -- 0.088 / -- 0.055 / 0.036 0.174 / 0.070	Commercial Grade A as received from supplier. cleaned with liquid detergent. mechanically polished. oxidized in air at red heat for 30 min.	--	5	Betz, Olson, Schurin, and Morris [1958]
Hastelloy B $\epsilon_{t,0}$ $(T = 83.3°K)$ 0.065 0.032	Aircraft grade, annealed condition finish with RMS rating of 15 microinches. finish with RMS rating of 2 microinches.	--	5	Betz, Olson, Schurin, and Morris [1958]

TABLE 3.5 TOTAL REFLECTANCE OF NICKEL AND NICKEL ALLOYS (continued)

Hastelloy C		Grade AMS 5530C, annealed condition	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$, T = 83.3°K	$\epsilon_{t,0}$, T = 422.2°K				
0.111	0.120	finish with RMS rating of 15 microinches.			
0.043	0.078	finish with RMS rating of 2 microinches.			
Inconel X			--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$, T = 83.3°K	$\epsilon_{t,0}$, T = 422.2°K				
0.055	0.110	as received from supplier.			
0.055	0.110	cleaned with liquid detergent.			
0.067	--	mechanically polished.			
0.067	0.130	oxidized in air at red heat for 30 min.			

TABLE 3.6 TOTAL REFLECTANCE OF SILVER

Reflectance	Sample Preparation	Radiation Source	Method	Reference
(1) $\rho_t = 0.9916$ (2) $\rho_t = 0.9918$ (T = 75.8°K) (3) $\rho_t = 0.9922$ (4) $\rho_t = 0.9924$	Electroplated	Black body at temperature: (1) 268°K (2) 300°K (3) 325°K (4) 367°K	4	Cline [1962]
(T = 76°K) (1) $\rho_t = 0.992$ (2) $\rho_t = 0.991$ (3) $\rho_t = 0.993$ (4) $\rho_t = 0.991$ (5) $\rho_t = 0.983$ (T = 20°K) (6) $\rho_t = 0.987$	(1) Sheet (2) Silver plate (careful preparation) nickel strike on stainless steel (3) Silver plate (careful preparation) nickel and copper strike on stainless steel (4) Allegheny Silver Spray Process on stainless steel (5) Plated on copper (6) Plated on copper	Source at 300°K	4	Fulk and Reynolds (1957b)
(T = 77.3°K) (1) $\rho_t = 0.9917$ (2) $\rho_t = 0.988$ (3) $\rho_t = 0.984$	(1) Silver-lume (2) Electroplate (unbuffed) (3) Dry buffed	Source at 300°K	4	Zimmerman [1955]
(1) $\rho_t = 0.977$ (T = 90°K) (2) $\rho_t = 0.964$	(1) Chemically deposited (2) Foil-polished	Source at 293°K	4	Blackman, Egerton, and Truten [1948]

TABLE 3.7 TOTAL REFLECTANCE OF STEEL AND VARIOUS STAINLESS STEELS

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
Steel $\rho_t = 0.904$ (T = 90°K)	Foil-dry, mechanically polished.	Source at 293°K	4	Blackman, Egerton, and Truten [1948]
Stainless Steel (1) $\rho_t = 0.952$ } (2) $\rho_t = 0.93$ } T = 76°K	(1) 0.005 inch type 302 sheet (2) commercial ball type 302	Source at 300°K	4	Fulk and Reynolds [1957b]
Stainless Steel Type 321	Grade MIL-S-6721A, annealed condition	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$: T = 83.3°K / T = 422.2°K				
0.044 / --	bright			
0.111 / 0.175	dull, finish of RMS = 6 microinches	--		
0.155 / --	dull, oxidized in air at red heat for 30 minutes			
0.036 / 0.090	finish with RMS rating of 2 microinches			

TABLE 3.7 TOTAL REFLECTANCE OF STEEL AND VARIOUS STAINLESS STEELS (continued)

Reflectance or Emittance	$\epsilon_{t,0}$ T = 83.3°K	$\epsilon_{t,0}$ T = 422.2°K	Sample Preparation	Radiation Source	Method	Reference
Stainless Steel Type 316			Grade MIL-S-5059A, annealed condition	--	5	Betz, Olson, Schurin, and Morris [1958]
	0.045	0.100	finish with RMS rating of 15 microinches			
	0.027	0.080	finish with RMS rating of 2 microinches			
Stainless Steel Type AM 350			Aircraft grade, subzero cooled and tempered.	--	5	Betz, Olson, Schurin, and Morris [1958]
			finish with RMS rating of 2 microinches.			
	0.161	0.110	--			
	0.111	--	cleaned with liquid detergent			
Stainless Steel Type 446			Grade QQ-5-763A, annealed condition.	--	5	Betz, Olson, Schurin, and Morris [1958]
	0.167	0.155	finish with RMS rating of 15 micrinches			
	0.158	--	finish with RMS rating of 2 microinches			

TABLE 3.7 TOTAL REFLECTANCE OF STEEL AND VARIOUS STAINLESS STEELS (continued)

Reflectance or Emittance		Sample Preparation	Radiation Source	Method	Reference
Stainless Steel Type 17-7PH		Grade MIL-S-25043A, annealed condition	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$					
T = 83.3°K	T = 422.2°K				
0.044	0.093	finish with RMS rating of 15 microinches.			
0.022	0.048	finish with RMS rating of 2 microinches.			
Stainless Steel Type PH15-7MO		RH950 condition	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$					
T = 83.3°K	T = 422.2°K				
0.044	0.074	finish with RMS rating of 15 microinches.			
0.022	0.080	finish with RMS rating of 2 microinches.			

TABLE 3.8 TOTAL REFLECTANCE OF TIN

Reflectance	Sample Preparation	Radiation Source	Method	Reference
$(T = 76°K)$ (1) $\rho_t = 0.987$ (2) $\rho_t = 0.98$	(1) 0.001 inch foil (2) Tinned copper ball	Source at 300° K	4	Fulk and Reynolds (1957b)
(1) Tin: $\rho_{t,0} = 0.9876$) (2) Tin + 1% Indium: $\rho_{t,0} = 0.9875$) (3) Tin + 5.4% Indium: $\rho_{t,0} = 0.9826$) T = 2.0 to 4.2° K	Electropolished. Inpurities in tin < .004% Indium: chemically pure	Black body at room temperature ($\lambda_{mean} \approx 14\mu$)	4	Ramanathan [1952]
$\rho_t = 0.962$ $(T = 90°K)$	Foil (0.0025 cm thick) Approximately equivalent to buffed surface.	Source at 293° K	4	Blackman, Egerton, and Truten [1948]

TABLE 3.9 TOTAL REFLECTANCE OF VARIOUS BRASSES

Reflectance	Sample Preparation	Radiation Source	Method	Reference
$\rho_t = 0.971$ $(T = 76°K)$	Yellow brass, 0.001 inch Shim stock (65% Cu, 35% Zn)	Source at 300°K	4	Fulk and Reynolds [1957b]
(1) $\rho_t = 0.90$ (2) $\rho_t = 0.89$ $\}$ $T = 77.4°K$	(1) Hand polished, some scratches (2) Partly oxidized, with gas flame	Source at 273°K	4	Ziegler and Cheung [1956]
$\rho_{t,0} = 0.9822$ $(T = 2.0$ to $4.2°K)$	Electropolished ("commercial" stock)	Black body at room temperature ($\lambda_{mean} \approx 14\mu$)	2	Ramanathan [1952]
$\rho_t = 0.954$ $(T = 90°K)$	Mechanically polished (64% Cu)	Source at 293°K	4	Blackman, Egerton, and Truten [1948]

TABLE 3.10 TOTAL REFLECTANCE OF VARIOUS METALS AND ALLOYS

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
Aluminum Bronze (4-7%) $\epsilon_{t,0}$ T = 83.3°K T = 422.2°K 0.041 -- 0.041 -- 0.038 0.030 0.058 0.080	Federal specifications QQ-B-667, Composition: Copper = 92-96% Aluminum = 4-7% Iron = < 0.5% as received from supplier. cleaned with liquid detergent. mechanically polished. oxidized in air at red heat for 30 min.	--	5	Betz, Olson, Schurin, and Morris [1958]
Aluminum Bronze (6-8%) $\epsilon_{t,0}$ T = 83.3°K T = 422.2°K 0.104 0.060 0.104 0.060 0.067 0.005 0.241 0.062	Federal specifications QQ-B-667, Composition: Copper = 88-92.5% Aluminum = 6-8% Iron = <3.5% Manganese = $\lesssim$ 1% as received from supplier. cleaned with liquid detergent. mechanically polished. oxidized in air at red heat for 30 min.	--	5	Betz, Olson, Schurin, and Morris [1958]
Cadmium $\rho_t = 0.97$ (T = 76°K)	Very mossy and smeared-looking plated surface	Source at 300°K	4	Fulk and Reynolds [1957b]

TABLE 3.10 TOTAL REFLECTANCE OF VARIOUS METALS AND ALLOYS (continued)

<table>
<tr><th>Reflectance or Emmittance</th><th>Sample Preparation</th><th>Radiation Source</th><th>Method</th><th>Reference</th></tr>
<tr><td><u>Chromium</u>
(1) $\rho_t = 0.92$ (T = 76°K)

(2) $\rho_t = 0.916$ (T = 77.4°K)</td><td>(1) Chromium plate on copper

(2) Bright, plated on monel cylinder</td><td>(1) Source at 300°K

(2) Source at 273°K</td><td>4</td><td>(1) Fulk and Reynolds [1957b]

(2) Ziegler and Cheung [1956]</td></tr>
<tr><td><u>Cobalt Alloy N-155</u>
<table>
<tr><th colspan="2">$\epsilon_{t,0}$</th></tr>
<tr><th>T = 83.3°K</th><th>T = 422.2°K</th></tr>
<tr><td>0.058</td><td>0.120</td></tr>
<tr><td>0.033</td><td>--</td></tr>
<tr><td>0.041</td><td>0.100</td></tr>
<tr><td>0.072</td><td>--</td></tr>
</table></td><td>as received from supplier.
cleaned with liquid detergent.
mechanically polished.
oxidized in air at red heat for 30 min.</td><td>--</td><td>5</td><td>Betz, Olson, Schurin, and Morris [1958]</td></tr>
<tr><td>Iron (Armco Ingot)
<table>
<tr><th colspan="2">$\epsilon_{t,0}$</th></tr>
<tr><th>T = 83.3°K</th><th>T = 422.2°K</th></tr>
<tr><td>0.010</td><td>--</td></tr>
<tr><td>0.222</td><td>0.465</td></tr>
</table></td><td>Finishing with RMS rating of 2 microinches

--
oxidized in air at red heat for 30 min.</td><td>--</td><td>5</td><td>Betz, Olson, Schurin, and Morris [1958]</td></tr>
</table>

TABLE 3.10 TOTAL REFLECTANCE OF VARIOUS METALS AND ALLOYS (continued)

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
<u>Iron</u> $\rho_t = 0.903$ (T = 90°K)	Electrolytic	Frequency band from 2 to 18 μ	2	Weiss [1948]
<u>Molybdenum</u>	Arc melted, unalloyed (Climax Molybdenum Co.)	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$: T = 83.3°K / T = 422.2°K				
0.033 / 0.025	as received from supplier.			
0.033 / 0.010	cleaned with liquid detergent.			
0.041 / 0.020	mechanically polished.			
0.079 / --	oxidized in air at red heat for 30 min.			
<u>Monel</u> (T = 77.4°K) $\rho_t = 0.89$	Hand polished--some scratches.	Source at 273°K	4	Ziegler and Cheung [1956]
<u>Platinum</u> $\rho_t = 0.904$ (T = 85°K)	--	Source at 290°K	--	Fulk and Reynolds [1957a]
<u>Rhodium</u> $\rho_t = 0.922$ (T = 76°K)	Rhodium plated on stainless steel.	Source at 300°K	4	Fulk and Reynolds [1957b]

TABLE 3.10 TOTAL REFLECTANCE OF VARIOUS METALS AND ALLOYS (continued)

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
Solder				
(1) $\rho_t = 0.97$ (T = 76°K)	(1) 50% Sn - 50% Pb, 0.002 inch surface on .005 in copper plate	(1) Source at 300°K	4	(1) Fulk and Reynolds [1957b]
(2) $\rho_t = 0.953$ (T = 77.4°K)	(2) 40% Sn - 60% Pb, surface applied with air-gas torch	(2) Source at 273°K		(2) Ziegler and Cheung [1956]
Tantalum	Pure metal.	--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$: T = 83.3°K; T = 422.2°K				
0.030; --	as received from supplier.			
0.030; 0.028	cleaned with liquid detergent.			
0.025; 0.030	mechanically polished.			
0.192; 0.420	oxidized in air at red heat for 30 min.			
Titanium Alloy C-110M		--	5	Betz, Olson, Schurin, and Morris [1958]
$\epsilon_{t,0}$: T = 83.3°K; T = 422.2°K				
0.014; 0.082	as received from supplier.			
0.014; 0.082	cleaned with liquid detergent.			
0.014; 0.082	mechanically polished.			
0.083; 0.110	oxidized in air at red heat for 30 min.			

TABLE 3.10 TOTAL REFLECTANCE OF VARIOUS METALS AND ALLOYS (continued)

Reflectance or Emittance	Sample Preparation	Radiation Source	Method	Reference
Tungsten $\rho_{t,0} = 0.901$ (T = 85°K)	Filament	Source at 300°K	--	Fulk and Reynolds [1957a]
Wood's metal (T = 77.4°K $\rho_t = 0.84$	Surface applied with air-gas torch.	Source at 273°K	4	Ziegler and Cheung [1956]
Zinc $\rho_t = 0.98$ (T = 76°K)	0.0065 inch foil	Source at 300°K	4	Fulk and Reynolds [1957b]

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